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(54) **Ultrasonic irradiation system.**

(57) An ultrasonic irradiation system has a transducer (1) which is composed of a plurality of elements divided at least in a circumferential direction of the face of the transducer (1) so that the phases of drive signals may be changed according to the respective circumferential positions of the oscillating elements. This permits the phases of the drive signals to be rotated by n rotations in the circumferential direction. As a result, an annular focal zone having a desired radius is formed, and the integrated values of sound waves in the circumferential direction may be substantially zero on the focal plane so that no unnecessary secondary focal zone is formed.

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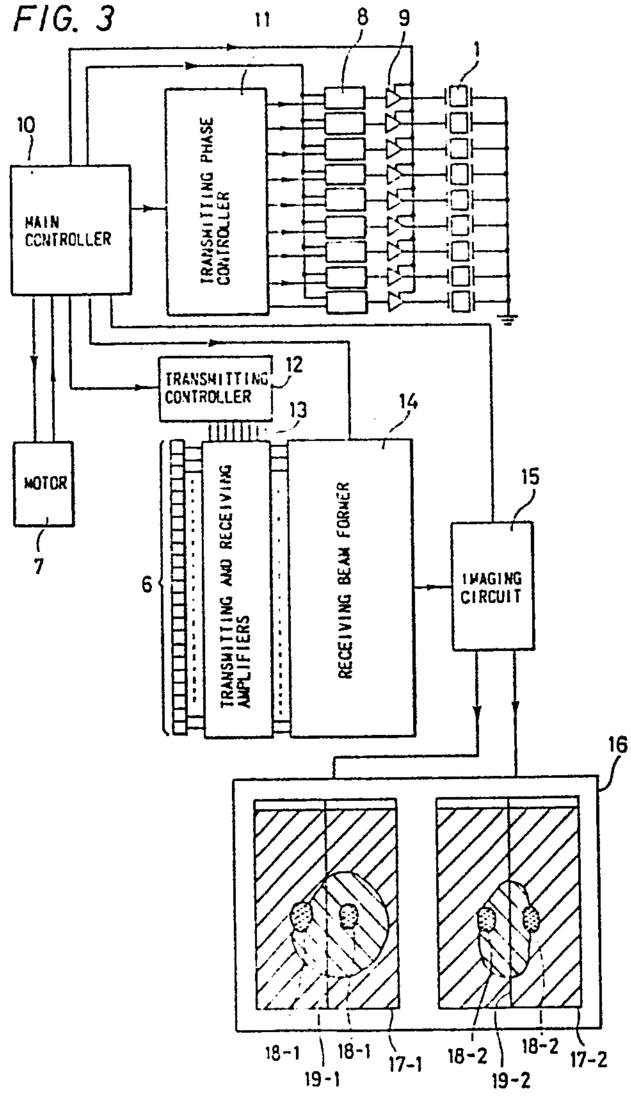
FIG. 3


11
8
9
1
10
MAIN CONTROLLER
TRANSMITTING PHASE CONTROLLER
TRANSMITTING CONTROLLER
12
13
14
MOTOR
7
6
TRANSMITTING AND RECEIVING AMPLIFIERS
RECEIVING BEAM FORMER
15
IMAGING CIRCUIT
16
18-1
19-1
18-1
17-1
18-2
19-2
18-2
17-2

ULTRASONIC IRRADIATION SYSTEM

The present invention relates to an ultrasonic irradiation system such as an ultrasonic heater, an ultrasonic chemical reaction accelerator, a sonicator, or an ultrasound therapy system suitable for remedy of malignant tumours.

In such systems, including those involving medical treatment, the ultrasound focal zone formed by a single spot focus may be too small, as compared with the target zone to be irradiated. To overcome this, it is known to provide an ultrasonic irradiation system in which an annular focal zone is formed by using an acoustic lens such as that disclosed in "Ultrasound in Med. & Biol." vol. 8, No. 2 (issued in 1982), pp. 177 to 184. However, this system has the defect that the position, size and shape of the irradiation cannot be controlled in dependence on the object to be irradiated with ultrasonic waves because they are fixed. Moreover, the system has a tendency that the ultrasonic waves spreading again from an annular focal zone A will reform a long column-shaped focal zone B on the centre axis of the annulus, as shown in section in Fig. 1. This tendency is sufficiently acute to be a serious problem when the diameter of the annulus is smaller than that of the ultrasonic probe. In the field of ultrasound therapy, for example, the formation of a secondary focal zone, in addition to the target zone, may adversely affect the normal internal tissues of a patient or may cause pain.

The present invention seeks to provide an ultrasonic irradiation system capable of forming a larger focal zone than a single spot focus which may also permit the area of that zone to be variable. It is also desired to form a larger focal zone than the single one without forming a secondary focal zone, in addition to the target zone.

According to the present invention, a focal zone, e.g. annular or elliptic, is formed on a focal plane by means of a transducer having an array of transducer elements so that the value of the integration of the sound pressure on the focal plane is negligibly small, compared with the integration of the absolute sound pressure.

According to the invention, sound waves may then be generated along an annular focal zone and the phase of their sound pressures may rotate in the circumferential direction. To achieve this, a transducer having a two-dimensional array of transducer elements may be used, and the phases of signals for driving the respective elements then rotate around the centre position of the transducer in the circumferential direction. To form the focal plane, on the other hand, the phases of the drive signals of the respective elements are also modified according to the position in the radial direction. The focal distance can be varied by adjusting the phases of the drive signals in the radial direction.

The adjustment of the phases of the drive signals in the radial direction is unnecessary if it is sufficient to fix the focal distance. Therefore, this focal plane can be formed either by using an acoustic lens or by making the transducer face concave. In this case, the transducer may be of radial array type in which a transducer plate of a circular or a similar shape is divided into a plurality of elements along the circle.

In order to control the size of the focal zone, on the other hand, the number of poles zn (n = 1, 2, 3, 4 and so on) of the drive signals in circumferential direction of the oscillator face is changed. The diameter of the annular focal zone is enlarged by increasing the polar number n.

Embodiments of the invention will now be described in detail, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 is a sectional view showing the probe and its focal zone produced by a known ultrasonic irradiation system, and has already been described;

Fig. 2 is a diagram showing the focal zone produced by an embodiment of the present invention;

Fig. 3 is a block diagram showing one embodiment of the present invention;

Figs. 4A and 4B, Figs. 6A and 6B, and Figs. 8A and 8B are respectively top and sectional views showing examples of a probe to be used in the present invention;

Fig. 5 is a diagram showing the focal zone formed by the probe of Figs. 4A and 4B;

Fig. 7, Figs. 9A and 9B, and Figs. 10A, 10B and 10C are respectively top views showing phase controls for the probes;

Figs. 11A, 11B and 11C are diagrams obtained by the phase controls of Figs. 10A, 10B and 10C;

Figs. 12A and 12B are a top and a sectional view respectively of a probe for use in another embodiment of the present invention;

Figs. 13A and 13B are diagrams showing sound waves obtained by the probe of Figs. 12A and 12B; and

Figs. 14A and 14B are a top and a sectional view respectively showing a probe for use in a further embodiment of the present invention.

Fig. 2 shows the pattern of a sound field formed by a representative embodiment of the present invention.

If the phase of the sound pressure of an annular focal zone on a focal plane P is deliberately modulated along the annulus so that the integration of sound pressure on P is substantially equal to zero, the acoustic energy necessary for forming annular focal zones A1 and A2 on the focal plane P can be concentrated without forming any secondary focal point B. In other words, the focal zones formed on the focal plane P are symmetric with respect to the centre axis so that the sound pressure on the axis is maintained at zero.

If, moreover, the point where the phase of the sound pressure is zero is rotated, as indicated by thick arrows in Fig. 2, the acoustic energy time-averaged on the annulus may be made uniform, to form the desired acoustic energy irradiation pattern.

The constructions of the probes shown in Figs. 4A and 4B, Figs. 6A and 6B, and Figs. 8A and 8B will now be described in detail. In all these examples of a probe suitable for use in the present invention, a transducer 1 made of piezoelectric ceramics and a second acoustic matching layer 3 made of a polymer are adhered to the front and back of a board 2 of light metal acting as a first acoustic matching layer, as a ground electrode and as a heat sink, respectively. A water bag 4 for acoustic coupling between the transducer and an object to be irradiated is attached to the second acoustic matching layer 3. In the probe of Figs. 4 and 6, the transducer 1 is divided into ring-shaped oscillating elements, each of which is radially divided into six oscillating elements. In the probe of Fig. 8, on the other hand, the oscillator is constructed by arraying a plurality of oscillating elements regularly two-dimensionally. Thus, the oscillator for irradiating sound waves to an annular focal zone is constructed of those plurality of oscillating elements. In all the examples of Figs. 4, 6 and 8, an auxiliary probe 6 for monitoring the irradiation is rotatably fitted in the central portion of the probe. That auxiliary probe 6 is of a small linear array type, in which the transducer elements have a resonance frequency between 100 kHz and 10 MHz, which is selected to be two or more times higher than the resonance frequency of the transducer 1. In a suitable example, the transducer 1 has a resonance frequency of 500 kHz whereas the auxiliary probe 6 has a resonance frequency of 3 MHz. The orientation of the array of the auxiliary probe 6 is controlled by means of a motor 7.

Moreover, a cooling pipe 5 is provided in the light metal board 2 of Figs. 4 and 6. In the example of Fig. 8, however, there is no need for a cooling pipe because the light metal board 2 directly contacts the acoustic coupling water confined in the water bag 4.

In the embodiment of Fig. 4, as shown in section in Fig. 5, the probe is given a finite curavature R so as to minimize the number of the transducer elements necessary for scanning the target zone by changing the radius and depth of the annular focal zone A. By thus setting the maximum direction of the directivity of the outer elements inward, the number of the elements required can be reduced to about one half the number needed with a planar probe. A similar effect can also be attained by combining a planar oscillator and an acoustic lens. This combination is shown in the example of Fig. 6, in which the acoustic lens is prepared by machining the light metal board 2 to form a Fresnel lens.

The overall construction of the system will be described with reference to Fig. 3. A main controller 10 supplies a signal to a transmitting phase controller 11, the signal determining the radius of an annular focal zone to be formed, the distance from the probe and the modulation mode along the annulus. As will be described later in detail, the drive phases of the respective elements of the transducer 1 in the transmitting phase controller 11 are determined by the signal from the main controller 10 until they are transferred as load data to m-bit counters 8. These m-bit counters 8 operate using those load data as their initial values, and they count clock pulses of a frequency of $2^m.f_0$ from the main controller 10. The m-bit counters 8 outputs their highest-bit signals, to produce irradiating transmission phase signals of a frequency f_0 which are fed to transmission amplifiers 9. These transmission amplifiers 9 amplify those transmitting phase signals to amplitudes determined by the signal from the main controller 10, and the amplified signals drive the respective elements of the transducer 1. As a result, the drive phases of the respective elements are individually controlled.

An example of the drive phases necessary for generating the sound field of the type shown in Fig. 2 will now be described. It is assumed here, as shown in Fig. 2; that the axis of rotational symmetry of the probe is the Z-axis; that cylindrical coordinates using the intersection between the probe and the Z-axis as an origin are designated at (Z, r, θ); that the coordinates of the centre of a k-th transducer element are designated at (Z_k, r_k,

θ_k); and that the coordinates of the annulus of the annular focal zone are designated by $Z = Z_F$ and $r = r_F$. With these assumptions, the drive phase φ_k (wherein k designates a natural number) to be given to each element is generally expressed by the following equation:

$$\varphi_k(Z_k, r_k, \theta_k, t)$$

$$= \alpha(Z_k, r_k) + \beta(\theta_k) + \omega_0 \cdot t \quad \text{-----} \ (3),$$

wherein ω_0 designates the angular frequency of the ultrasound waves to be transmitted.

In the right-hand side of the equation for determining the drive phase, the function α of (Z_k, r_k) provides factors for determining the depth Z_F of the focal plane and the radius r_F of the annular focal zone. Two methods exist for calculating the function α. One method is to determine the drive phase of each element such that the sound waves may converge at the position (Z_F, r_F) of the annulus in the section of the probe. According to this method, the function α is given by the following equation:

$$\alpha(Z_k, r_k)$$

$$= 2\pi/\lambda_0 \left[\sqrt{(Z_k - Z_F)^2 + (r_k - r_F)^2} - Z_F \right] \ \text{---} \ (4).$$

Another method is to form the annular focal zone by modulating the driving phases, which are calculated to locate the focal point at $(Z_F, 0)$, by a further modulation by changing the drive polarity of each element. In order to consider what drive polarity is to be given, it is convenient to invert the time axis in the propagation of the sound waves. Since the sound wave A by the annular sound source having a radius r_F is expressed by the following equation:

$$A \propto J_0\left(\frac{2\pi r_F}{\lambda_0}\sin\theta\right) \fallingdotseq J_0\left(\frac{2\pi r_F}{\lambda_0}\theta\right) \quad \cdots (5)$$

(wherein: J_0 designates the 0-th order Bessel's function; and θ designates an azimuth angle). The sound field is generally proportional to J_0 $(2\pi\ r_F/\lambda_0 \cdot r_k/Z_F)$ on a circumference of a radius r_k on the face of the probe spaced at a distance Z_F from the focal plane. Therefore, the annular focal zone of the radius r_F from the focal plane. Therefore, the annular focal zone of the radius r_F at the distance Z_F from the probe can be formed by giving the following drive phase to each element. If the h-th zero point of the 0-th order Bessel's function is designated at a_h and if the following equation holds:

$$r_c = \frac{\lambda_0 Z_F}{2\pi r_F} \quad \cdots (6)$$

i) $r_k < a_1 r_C$ or $a_{2h} r_C < r_k < a_{2h+1} r_C$:

$$\alpha(Z_k, r_k) = \frac{2\pi}{\lambda_0}\left[\sqrt{(Z_k - Z_F)^2 + r_k^2} - Z_F\right] \cdots (7)$$

ii) $a_{2h-1}r_C < r_k < a_{2h}r_C$:

$$\alpha(Z_k, r_k) = \frac{2\pi}{\lambda_0}\left[\sqrt{(Z_k - Z_F)^2 + r_k^2} - Z_F\right] + \pi \quad \cdots (8)$$

(wherein h designates a natural number).

If the probe has a constant radius of curvature R, as shown in Fig. 4, the following equation holds in the equations (4), (7) and (8):

$$Z_k^2 - 2RZ_k + r_k^2 = 0 \quad \cdots (9)$$

If, on the other hand, the probe has an infinite radius of curvature, as shown in Fig. 8, the following equation holds:

$$Z_k = 0 \quad \cdots (10)$$

With either method, the depth Z_F of the focal plane and the radius r_F of the annular focal zone are determined by the term α of the phase in dependence on the radial position r_k of the oscillating elements.

On the righthand side of the equation determining the drive phase, the term β of the function of Θ_k is calculated in the following manner. In the case of the dipolar annular focal zone of Fig. 2, the function β is given by the following equation:

$$\beta(\theta_k) = \theta_k \quad \cdots (11)$$

In other words, the phase of the drive signal of each element is rotated 360 degrees for one rotation in the circumferential direction on the face of the probe. In the probe of Fig. 4 or 6, the distribution of the phase of each element has the shape shown in Fig. 7. The distribution for the embodiment of Fig. 8, however, has the shape shown in Fig. 9. In this embodiment, the phase distribution is rotated whilst the phase difference between the elements is maintained. Since the equi-phase plane of the sound pressure is rotated in the direction of the arrow, as shown in Fig. 2, on the focal plane P, that rotation of the phase distribution causes the energy of the sound waves to be distributed uniformly in an annular form as a time elapses.

Although the above description has been concerned with the case in which a dipiar focal zone is formed, the polar number can be increased to form a focal zone of 2n poles. In this case, the term $\beta(\theta_k)$ of the equation (3) is given by the following equation:

$$\beta(\theta_k) = n\,\theta_k \quad \cdots (12)$$

Thus the drive phase φ_k obtained from equation (3) is quantitized in units of $2\pi/2^m$, so that the lower m bits are outputted from the transmitting phase controller 11 to produce the load data of the m-bit counters 8. As a result, each element is driven by the phase which is designated by φ_k.

In the example of Fig. 7, the number of driving amplifiers 9 in Fig. 3 can be decreased by half by changing the piezoelectric polarity of transducer elements 1. For instance, positive polarity is given to '0', 'π/3', and '2π/3' elements in Fig. 7, negative polarity is given to others, and point symmetric pairs of elements are electrically combined by pairs.

The embodiment of Fig. 3 is equipped with an irradiation monitoring imaging means in addition to the irradiating transmitting phase means, as will now be described. In Fig. 3, there is shown an imaging auxiliary probe 6, and a motor 7 for rotating the probe 6 on the Z-axis so that a plurality of ultrasound echo tomograms necessary for positioning the irradiation target can be formed. Each of the elements of the auxiliary probe 6 is connected, through a transmitting and receiving amplifier 13, to a transmitting controller 12 and a receiving beam former 14. The drive signals, which have their phases controlled for each element by the transmitting controller 12, are repeatedly applied through the transmitting and receiving amplifiers 13. As a result, an ultrasound beam for imaging by linear or sector scanning is repeatedly emitted from the probe 6 into a predetermined part of the object. This ultrasound beam has a frequency equal to the resonance frequency of the auxiliary probe 6.

Both the echo signals generated due to discontinuity of the acoustic impedance in the object and the harmonics signals generated due to the acoustic nonlinear effect by the irradiating ultrasound waves are received by the respective elements of the imaging auxiliary probe 6, amplified by the transmitting and receiving amplifiers 13, and focused by the receiving beam former 14. As a result, signals are generated which are indicative of the time changes in the intensity of the reflected signals or the harmonics signals based on the received beam which is sequentially scanned for imaging by linear or sector scanning. These signals are fed through an imaging circuit 15 to a display unit 16 so that the generated positions and the ultrasound intensities of the echo signals or the harmonics signals are displayed through the imaging circuit 15 in the display frame of the display unit 16. The receiving beam former 14 is equipped with electronic scanning means, electronic focusing means, and also a band-pass filter so that its centre frequency is synchronised with the imaging ultrasound frequency, which is more than twice as high as the irradiating ultrasound frequency. This makes the ultrasonic imaging operation possibile without any interference, even during ultrasonic irradiation. The display frame stores and displays two images, as designated at 17-1 and 17-2, so as to make it convenient to position the irradiation target. Therefore, the operator operates the auxiliary probe by means of the motor 7 so that the tomograms taken in two arbitrary directions can be monitored by means of the display unit 16. Moreover, the monitor unit of the present embodiment superposes the tomographs of the object to display the focal zone of the ultrasound beam emitted from the oscillator 1 in the form of markers (as designated at 18-1 and 18-2 in Fig. 3). The imaging circuit 15 generates the marker signals indicating the section of the focal zone by using the signals indicating the depth and radius of the annular focal zone from the main controller 10 and feeds them to the display unit 16. Markers 19-1 and 19-2 indicate the positions of the centre axis of the probe.

By this imaging means, the following kinds of irradiation monitoring operations may be accomplished:

(1) The irradiation target may be identified and positioned by the ultrasonic imaging;

(2) The movement of the irradiation target may be detected, so that the irradiation zone may be moved in accordance with the target movement detected;

(3) The change in the acoustic impedance and in the sound velocity due to the temperature rise of the irradiation zone may be observed by measuring the intensity and the echo signal reflected from the irradiation zone;

(4) The harmonics waves generated in the irradiation zone by acoustical non-linear effects may be observed; and

(5) The harmonics waves generated in a so-called "hot spot" other than the target zone may be monitored.

Operation 1 has the advantage that it is not significantly influenced by refraction, even if sound velocity has a distribution in the human body, because the target is positioned by ultrasound waves which are similar to the irradiated waves and not by other means such as X-rays. Operation 2 makes use of the high speed of the ultrasound pulse echo imaging and is particularly suitable for electronic scanning type ultrasonic imaging means. Since movement of the irradiation target in three dimensions has to be detected, three-dimensional scanning with the ultrasound beam is necessary using a two-dimensional array type probe or by combining electronic scanning and mechanical scanning. Operation 3 observes changes in the reflected echo intensity, which is caused by changes in the acoustic impedance or the product of the sound velocity and the specific gravity both changing. Such changes result when the temperature of a substance in the irradiated zone is raised by absorption of the ultrasound wave. Operation 3 also detects changes in the reflected echo phase, which are caused by changes in sound velocity.

Thus, operation 3 is particularly effective in monitoring ultrasound heating. This method is partly disclosed on p. i.788 of "American Acoustics Report", vol. 15, No. 11 and in US-A-4,566,459.

The non-linear acoustic parameter A/B of a substance or cavitation in the irradiation zone causes the generation of harmonics components of the irradiating ultrasound waves. These are observed by operation 4 to provide information concerning the intensity and action of the ultrasound waves in the generation zone. If the waves having a relatively high reflection intensity are present in the irradiation target medium of the ultrasound waves, standing waves may be produced in the irradiation target medium to cause a so-called "hot spot" in parts of the medium other than the irradiation target zone. This unintended irradiation zone may be dangerous, particularly when the present invention is used in medical treatment so that it has to be avoided by careful monitoring.

Operation 5 monitors hot spots by observing the harmonics waves which are generated by the non-linear acoustic effect.

In order to carry out operations 4 and 5, it is necessary to stop the operation of the transmitting controller 12 thereby to detect only the harmonics waves which are geneated as a result of the irradiation of the sound waves using the probe 1. On the other hand, if a colour display unit is used as the display unit 16 and if the imaging circuit 15 generates display signals of different colours when the amplitude of the harmonics waves detected exceeds a predetermined allowable limit, this is more preferable as it immediately attracts the attention of the operator.

In the embodiment thus far described, the depth Z_F and radius r_F of the annular focal zone are determined by the phase adjustment (i.e. the term of $\alpha(Z_k, r_K)$ of equation (3)) according to the radial position r_k of the drive signal of the divided transducer 1. However, the radius r_F can also be controlled by the polar number (i.e. zn of equation (12)) of the rotations of the drive signals along the circumferential position of the oscillator. Therefore, the term of $\alpha(Z_k, r_k)$ of the equation (3) may be determined by the following equation, rather than by equation (4):

$$\alpha(Z_k, r_k)$$
$$= 2\pi/\lambda_0 (\sqrt{(Z_k - Z_F)^2 + r_k^2} - Z_F) \text{ ----------- } (13)$$

Equation (13) implies that the drive phase determined by the radial position r_k of the elements of the probe 1 may be calculated so that it is focused in the centre position of the focal plane at the desired depth Z_F.

When the probe of Fig. 8 is used, on the other hand, the drive phase may be inverted into a stripe form at the position of the two-dimensional array, rather than adjusting the drive phase according to the element position of the probe in the circumferential direction, as expressed by the equation (11). Then, the drive phase $\mathcal{J}_k$ of the probe element located at (Z_k, r_k, θ_k) is expressed by the following equation:

$$\varphi_k(Z_k, r_k, \theta_k)=\frac{2\pi}{\lambda_0}\left(\sqrt{(Z_k-Z_F)^2+r_k^2}-Z_F\right)$$
$$+\gamma(Z_k, r_k, \theta_k)+\omega_0 t \quad \cdots (13)$$

Here, the phase denoted by γ is shown in Figs. 10A, 10B and 10C, for example. By thus controlling the drive phase, a plurality of spots of different polarities can be formed simultaneously on the focal plane P, as shown in Figs. 11A, 11B and 11C. If irradiation is carried out whilst simultaneously switching the modes of Figs. 11A, 11B and 11C, the ultrasound wave energy can also have an annular time averaged distribution. By using a specified one of the modes of Figs. 11A, 11B and 11C, moreover, it is possible to form an ultrasound wave energy distribution which is suitable for a rotationally asymmetric irradiation target zone.

One feature that the examples of Figs. 7, 9 and 10, which show the distributions of the phase of the sound pressures on the faces of the transducer elements of a two-dimentional array type ultrasound transducer, have in common is that the drive phases of the respective elements are controlled so that the integral of their value is substantially negligible compared with the integral of their absolute values. This control provides an effective method for forming a sound field in which the integral of the sound pressure can be substantially neglected in comparison with the integral of the absolute value of the sound pressure on the focal plane.

As a result, the annular focal zone can be formed without forming the secondary focal zone B shown in Fig. 1.

Figs. 12A and 12B show the structure of a probe for use in a system being a further embodiment of the present invention. This probe has a fixed focal point using an acoustic lens to replace the control of the drive phase using the term $\beta(Z_k, r_k)$ of equation 3 and forms an annular focal zone. The transducer 1 for the sound wave transmission is divided into a plurality of annular piezo-electric elements T_1, T_2, - - -, and T_N having an internal radius r_0 and an external radius r_1. These elements are attached to the back of an acoustic lens 2 having a focal length Z_F. Also shown in Fig. 12B is a water bag 4.

If the transducer elements are considered in polar coordinates (r, θ), the angular coordinates of the i-th element are designated at θ_i and the amplitude of the drive signal is designated at $A(\theta_k)$, then the drive signal is controlled to satisfy the following equation:

$$A(\theta_k) = A_0 e^{j[n(\theta_k + \beta_1(\theta_k)) - \omega_0 t]} \quad - - - - \; - \; (14).$$

Thus the control is such that the phase of the drive signal proceeds on the annular transducer in the circumferential direction at an angular velocity ω_p given by the following equation:

$$\omega_p = \omega_0/n \cdot (1 + \beta_1'(\theta_k)) \quad - - - - - - - \; (15)$$

Here: ω_0 designates the angular velocity of the ultrasound waves; n designates the number of phase rotation per rotation in the circumferential direction $\beta_1'(\theta_k)$ designates a function expressing the azimuth modulation of the phase angular velocity; and A_0 designates a constant.

For simplicity, the sound field B on the focal plane in the absence of the modulation $\beta_1'(\theta_k)$ will now be calculated. If the polar coordinates on the focal plane are designated at $(R, \textcircled{H})$, if the wave number of the ultrasound waves is designated at k, and if the following equation holds:

$$K_F = kR/Z_F \quad \text{- - - - - - - - - - - - - - - - - -} \quad (16),$$

then the following equation is obtained:

$$B = \int_{r_0}^{r_1} \int_0^{2\pi} A(\theta) e^{jK_F r \cos(\theta - \textcircled{H})} r d\theta dr$$

$$= A_0 e^{j[n(\textcircled{H} + \pi/2) - \omega t]} \int_{r_0}^{r_1} \int_0^{2\pi} e^{j(n\theta - K_F r \sin\theta)} d\theta dr$$

$$= A_0 e^{j[n(\textcircled{H} + \pi/2) - \omega t]} \int_{r_0}^{r_1} J_n(K_F r) 2\pi r d\theta \quad \text{- - - -} \quad (17).$$

If $r_2 = 2/3 \cdot (r_1^3 - r_0^3) / (r_1^2 - r_0^2)$, the equation (17) can be approximated into the following form:

$$B = A_0 e^{j[n\textcircled{H} + \pi/2) - \omega t]} \cdot \pi(r_1^2 - r_0^2) J_n(k_F r_2)$$

$$\text{- - -} \quad (18).$$

In other words, the sound field B has a radial distribution with the form of an n-th order Bessel's function. As a result, annular focal zones of different radii can be formed by changing the phase rotation number n.

Figs. 13A and 13B show the sound pressure distribution (in absolute values) of the sound field on a focal plane, which is established for an ultrasound frequency of 0.5 MHz, a transducer having an internal radius of r_0 = 20 mm and an external radius r_1 = 60 mm, a focal length of Z_F = 80 mm and a probe having an element number N = 64, and when the phase rotation number n of the drive signal per rotation is set at n = 4 and n = 8. It is found that the radius of the focal zone on the focal plane is substantially proportional to the phase rotation number n.

Furthermore, an elongated annular focal zone is formed by modulating the angular velocity ω_p given by equation (15) using the modulation term $\beta_1(\theta_k)$. For example, when the transducer in Fig. 12A and 12B is driven by the signal with n = 8 and

$$\beta_1(\theta_i) = 0.15 \sin 2\theta, \quad --- \quad (19)$$

an oval-shaped focal zone with an aspect ratio 1.35 is formed on the focal plane.

The arrangement of Fig. 13 shows the use of the acoustic lens for geometrical focusing (i.e. to determine the focal length Z_F). However, geometrical focusing can also be achieved by making the shape of the transducer elements concave.

In the arrangements discussed above, the shapes of the transducers were circular or formed a regular polygon. This invention can also be applied to the transducers with other types of shapes such as elongated circles or elongate polygons. Also, these arrangements form the annular focal zone and control its diameter by using a probe having a two-dimensional or radially divided array of elements and by rotating the phases of the driving signals in the circumferential direction. However, the formation of the annular focal zone and the control of the zone radius can also be achieved by using an (annular array) probe composed of a number of multi-ring-shaped transducer elements.

Fig. 14 shows this arrangement, in which reference numerals 1-1, 1-2, 1-3, - - -, and 1-9 designate transducer elements divided into a multiplicity of rings, with the parts being indicated by the same numerals as those of the arrangement of Fig. 4. If cylindrical coordinates are considered with the rotationally symmetric axis of the probe located on the Z axis and an origin located at the centre of the probe and if the coordinates of a k-th transducer element are $Z = Z_k$ and $r = r_k$ and the coordinates of the annulus of the central portion of an annular focal zone are $Z = Z_F$ and $r = r_F$, the phase φ_k of the drive signal to be fed to that k-th transducer element is given by the following equation:

$$\varphi_k = \frac{2\pi}{\lambda_0}\left[\sqrt{(Z_k - Z_F)^2 + (r_k - r_F)^2} - Z_F\right] \quad \ldots(20)$$

Here, λ_0 designates the wavelength of the irradiation ultrasound waves.

Thus, in conclusion, the present invention proposes that the system has a control circuit for controlling the phases of the drive signals such that the modulus or root mean square value of the integral over the focal plane of the sound pressures of the sound pressure regions is negligible compared with the integral of the modulus or root mean square value of the sound pressures over the focal plane.

When the field pattern is static, this has the effect that the value of the integral over the focal plane of the sound pressures of the sound pressure regions generated by the transducer is negligible compared with the integral over each sound pressure region of the sound pressure of that sound pressure region at any time. When the field pattern is not static however, for example when the transducer illustrated in Fig. 12 A and B is driven with the signal in equation (14), the field pattern rotates in the order of magnitude of the ultrasound frequency. Thus the sound pressure P* on the focal plane S is controlled to satisfy the following inequality.

$$\left| \iint_S P^* \, dxdy \right| \ll \iint_S |P^*| \, dxdy \qquad (1)$$

where $P^* = P_0(x,y)e^{jwt}$ (2)

$P^* = P_0(x,y)$ (3)

Alternatively, the following expression could be used:

$$\frac{1}{\sqrt{h_1}}\left|\iint_S P^* \, dxdy\right| \ll \sqrt{\iint_S h_1 |P^*|^2 \, dxdy} \qquad (24)$$

with the same effect.

CLAIMS:

1. An ultrasonic irradiation system comprising:

a transducer (1) having a generally circular shape and being divided into a plurality of elements at least in a circumferential direction, the transducer (1) being adapted to generate a plurality of sound pressure regions on a focal plane;

a drive circuit (8) for generating drive signals for driving each of the elements, respectively;

characterised in that:

the system has a control circuit (10,11) for controlling the phases of the drive signals such that the modulus or root mean square value of the integral over the focal plane of the sound pressures of the sound pressure regions is negligible compared with the integral of the modulus or root mean square value of the sound pressures over the focal plane.

2. An ultrasonic irradiation system according to claim 1, wherein the control circuit (10,11) is adapted to control the phases of the respective drive signals of the transducer elements such that the phases of the drive signals are rotatable n rotations on the face of said transducer (1) in the circumferential direction.

3. An ultrasonic irradiation system according to claim 2, wherein the control circuit (10,11) is adapted to rotate the distribution of the respective drive phases of the oscillating elements while holding constant the mutual relationships between the drive phases.

4. An ultrasonic irradiation system according to any

one of claims 1 to 3, wherein the transducer (1) includes geometric focusing means.

5. An ultrasonic irradiation system according to claim 4, wherein the geometric focusing means is an acoustic lens having a predetermined focal point.

6. An ultrasonic irradiation system according to claim 4, wherein the geometric focusing means is means for making the face of the oscillator concave.

7. An ultrasonic irradiation system according to claim 1, further comprising:

an array type monitoring probe at the centre of the face of the transducer (1); and

imaging means for imaging by means of sound waves from an object by electronic linear or sector scanning of the array type probe.

8. An ultrasonic irradiation system according to claim 7, wherein the array type probe is driven by a signal having a frequency at least twice that of the drive signals for driving the transducer (1).

9. An ultrasonic irradiation system comprising:

a transducer (1) having a generally circular contour and being divided into a plurality of elements in both circumferential and radial directions;

a drive circuit (8) for driving each of the elements respectively; and

a control circuit (10,11) for controlling the phases of drive signals for driving the elements, respectively, wherein the control circuit (10,11) is adapted to control the phases of the respective drive signals for driving the transducer elements such that sound waves may be converged in a desired annular focal zone.

10. An ultrasonic irradiation system according to claim 9, wherein the control circuit (10,11) is adapted to determine the term of a phase adjustment corresponding to the radial positions of the elements with respect to the distance to, and the radius of, the focal plane of the annular focal zone and is adapted to control the phases of the respective drive signals for driving the elements such that the phases of the drive signals are rotatable through n rotations in the circumferential direction of the face of the transducer (1).

11. An ultrasonic irradiation system according to claim 9, wherein the control circuit (10,11) is adapted to determine the term of a phase adjustment corresponding to the radial positions of the elements for converging sound waves at the centre position of the focal plane of the annular focal zone and is adapted to control the phases of the respective drive signals of the elements such that the phases of said drive signals are rotatable through n rotations in the circumferential direction of the face of the transducer (1).

12. An ultrasonic irradiation system comprising:

a transducer (1) having a plurality of elements arranged in a two-dimensional array;

a drive circuit (8) for driving the elements respectively; and

a control circuit (10,11) for controlling the phases of drive signals for driving the elements, respectively, wherein the control circuit (10,11) is adapted to determine the term of a phase adjustment corresponding to the respective radial positions of transducer elements such that sound waves are convergable at the centre position of the focal plane of a desired annular focal zone, and is adapted to reverse sequentially the polarities of the drive signals in a predetermined direction of the two-dimensional array.

13. An ultrasonic irradiation system comprising:

a transducer (1) having a plurality of elements arranged in an annular array;

a drive circuit for driving the elements respectively; and

a control circuit (10,11) for controlling the phases of drive signals for driving said elements, respectively, wherein the control circuit controls the phases of the respective drive signals of the transducer elements such that sound waves are convergable toward an annular focal zone having a desired radius and a desired depthwise position.

FIG. 1 PRIOR ART

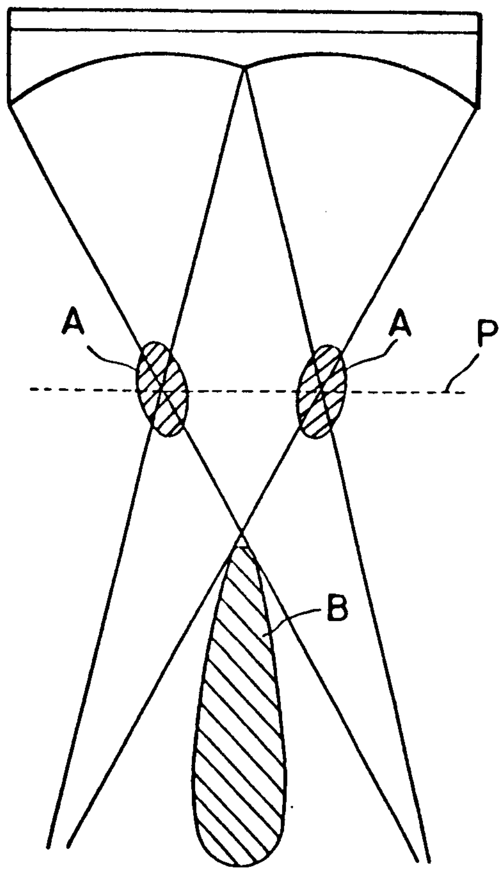


FIG. 2

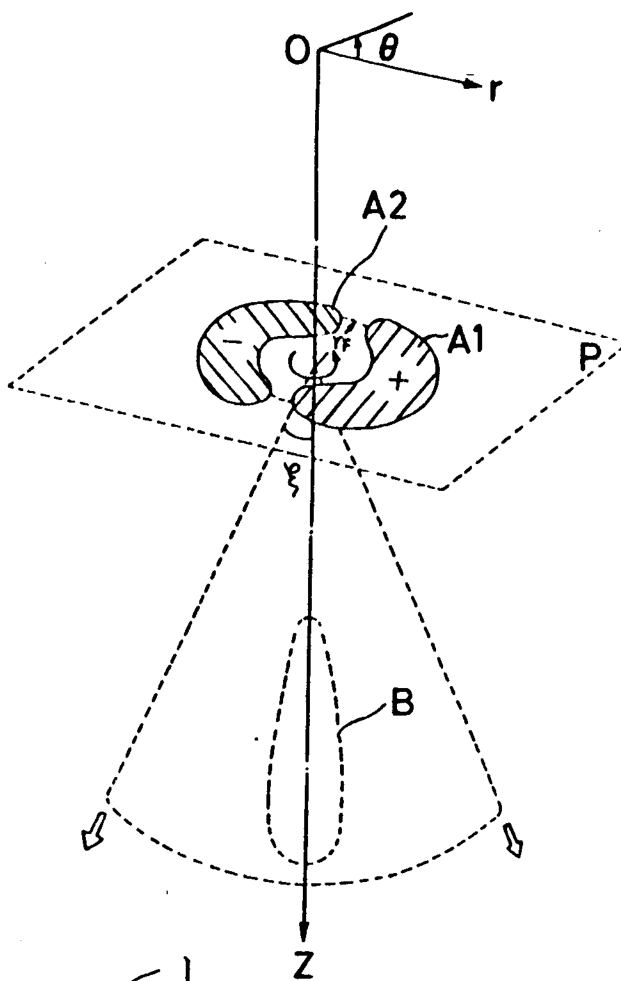


FIG. 5

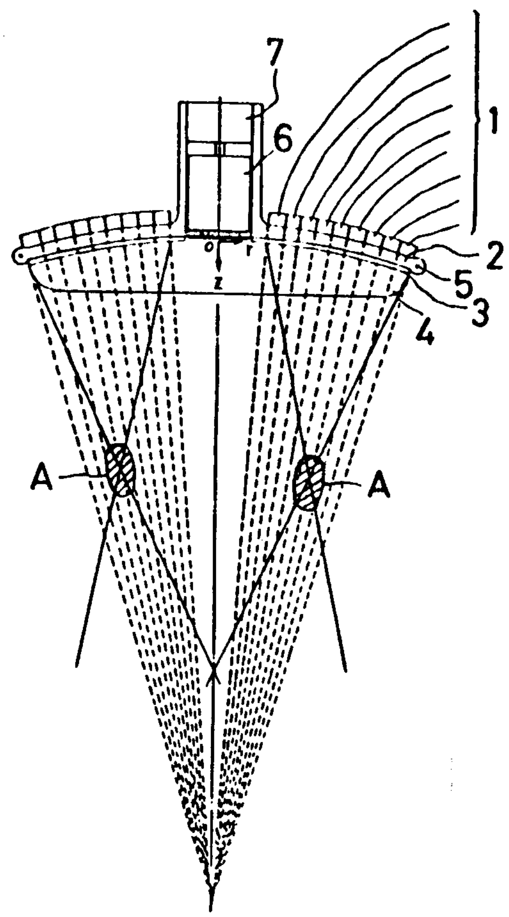
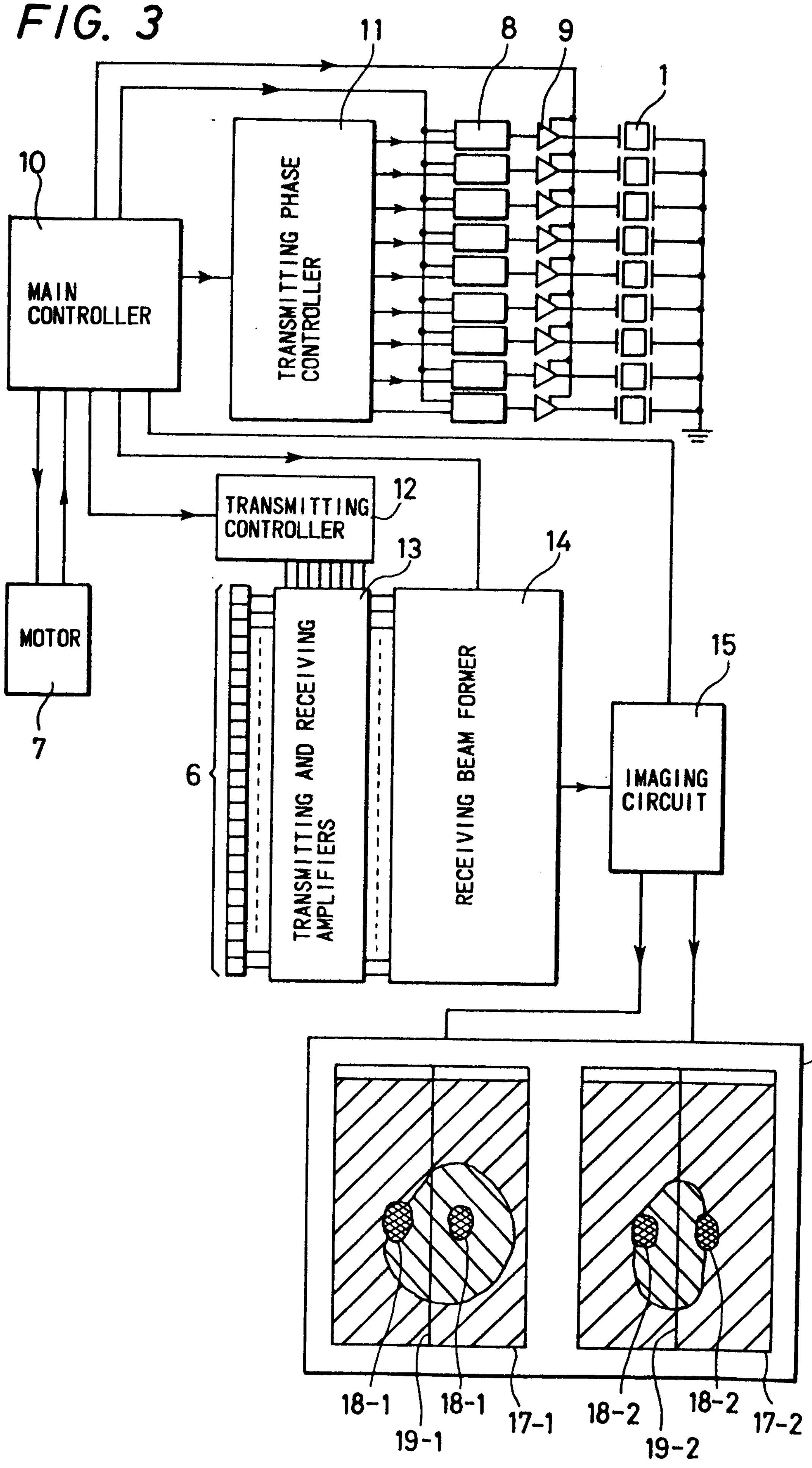


FIG. 3



11
8
9
1
10
MAIN CONTROLLER
TRANSMITTING PHASE CONTROLLER
TRANSMITTING CONTROLLER
12
13
14
MOTOR
7
6
TRANSMITTING AND RECEIVING AMPLIFIERS
RECEIVING BEAM FORMER
15
IMAGING CIRCUIT
16
18-1
18-1
19-1
17-1
18-2
19-2
18-2
17-2

FIG. 4A

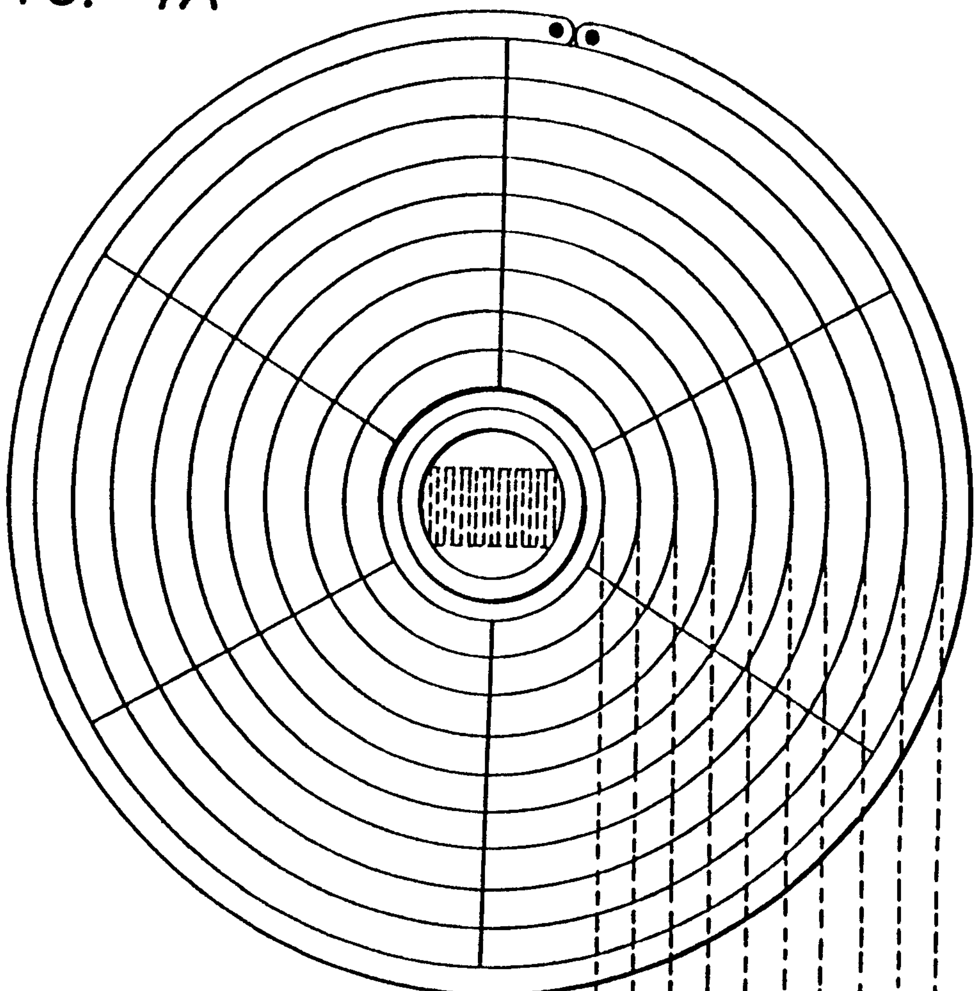


FIG. 4B

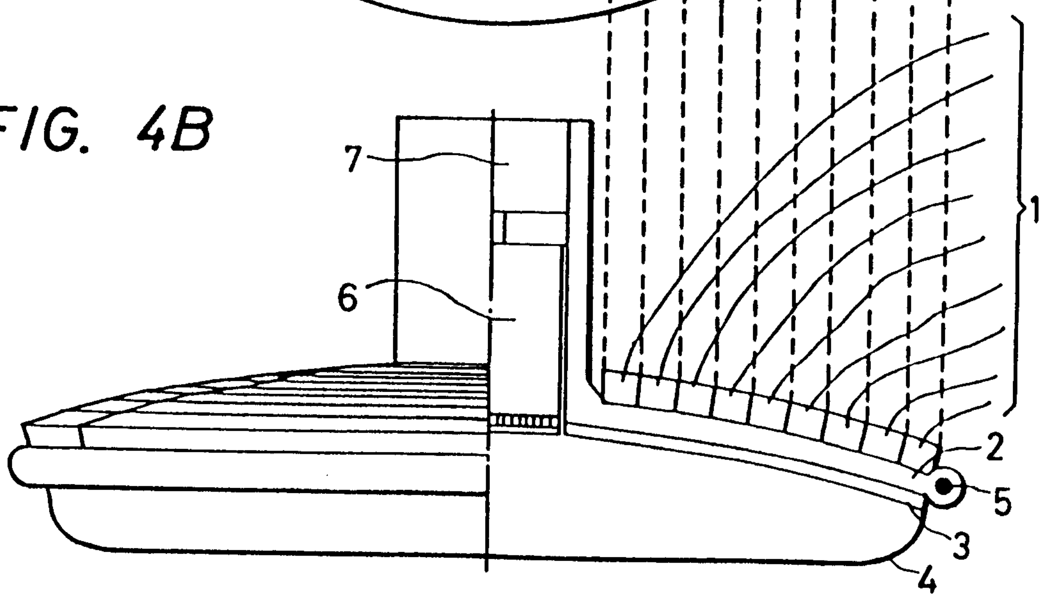


FIG. 6A

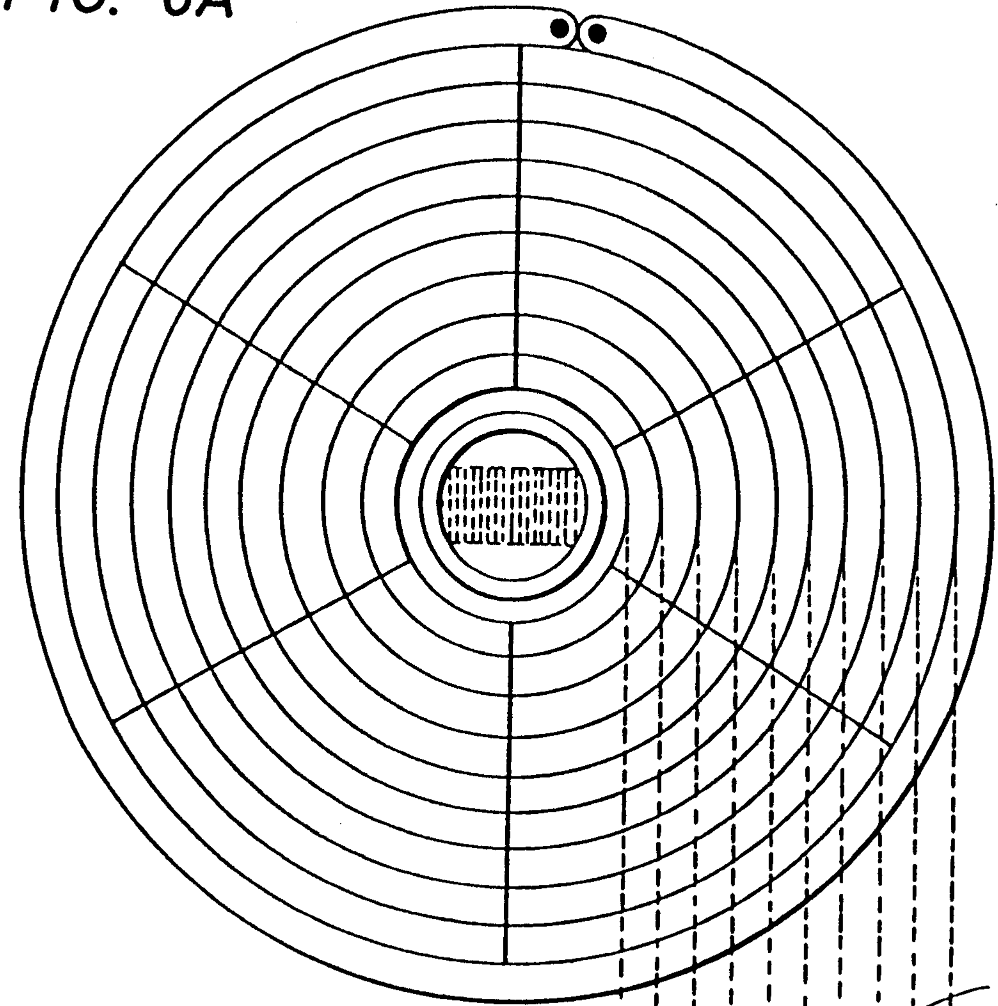


FIG. 6B

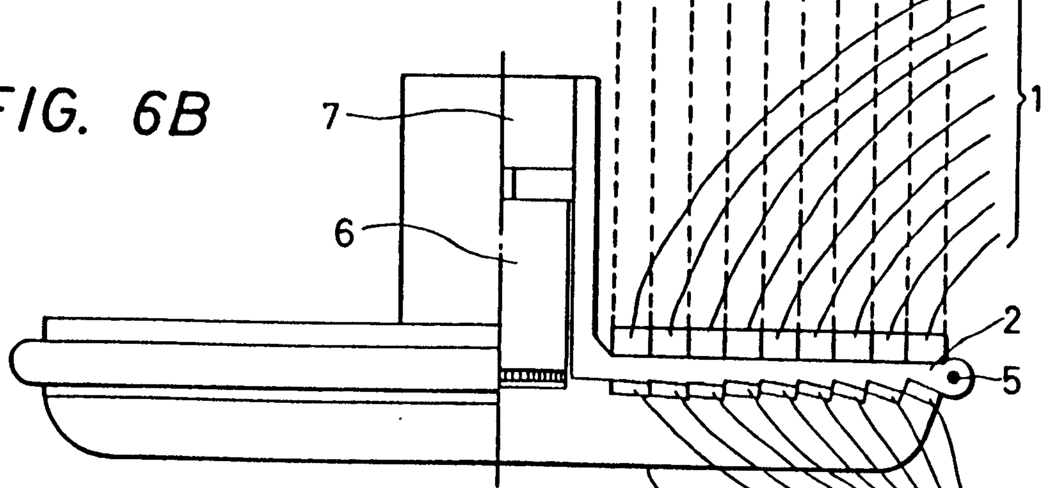


FIG. 7

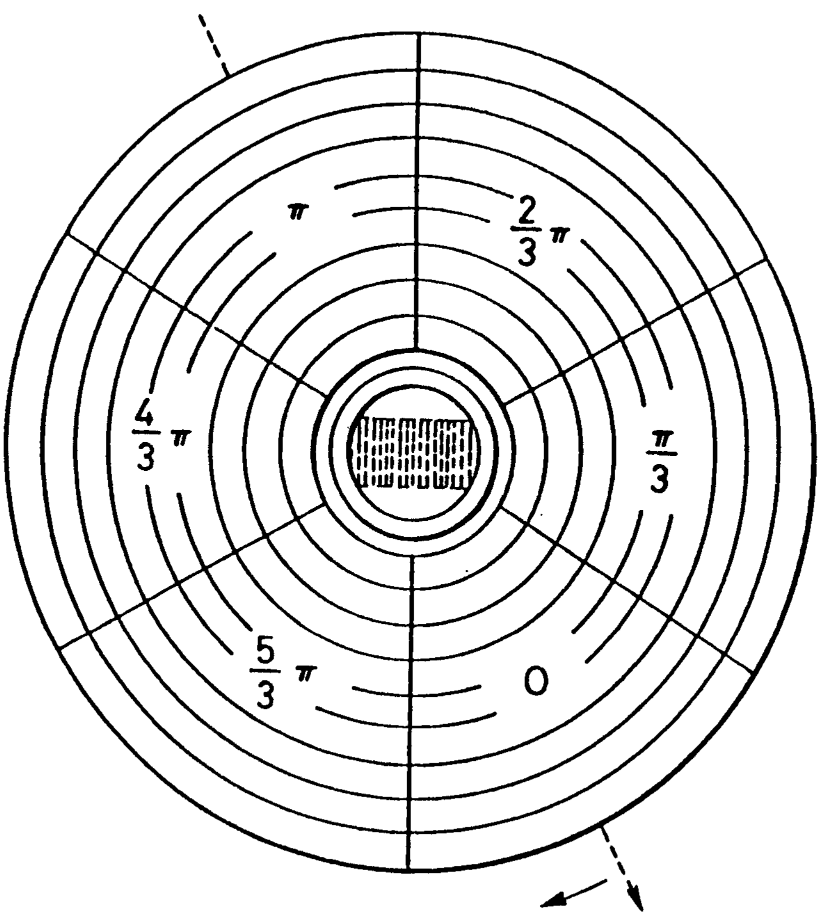


FIG. 8A

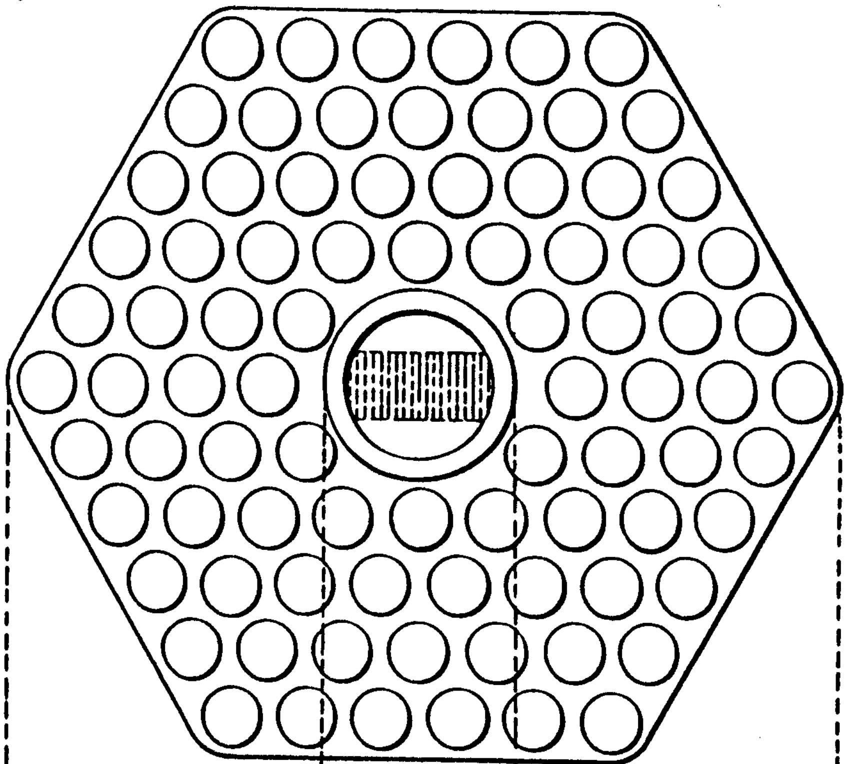


FIG. 8B

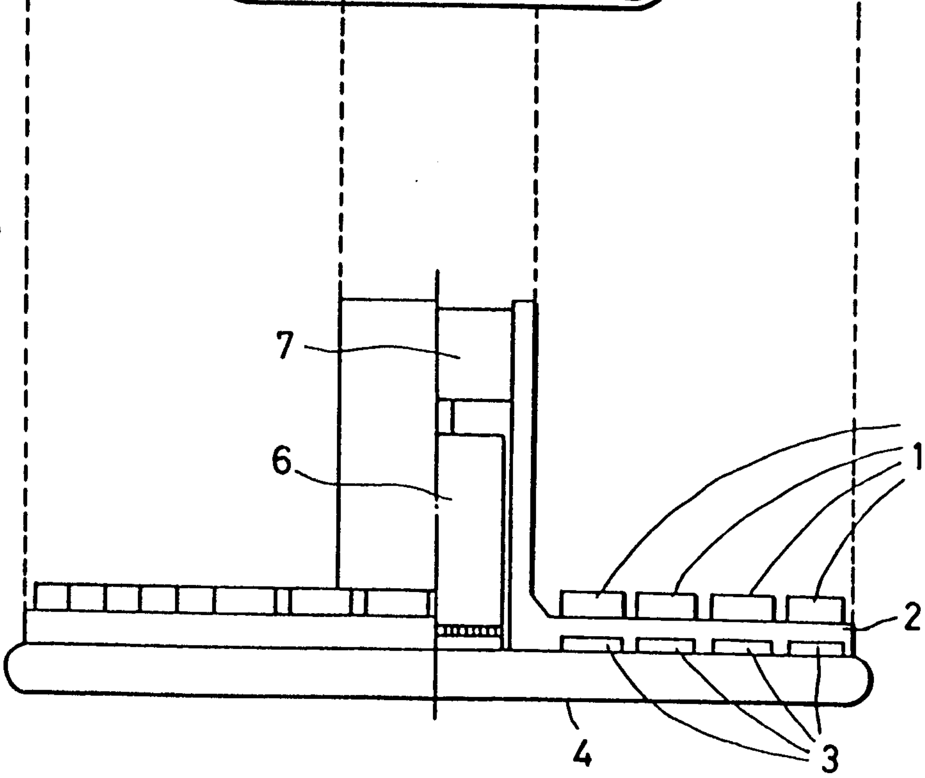


FIG. 9A

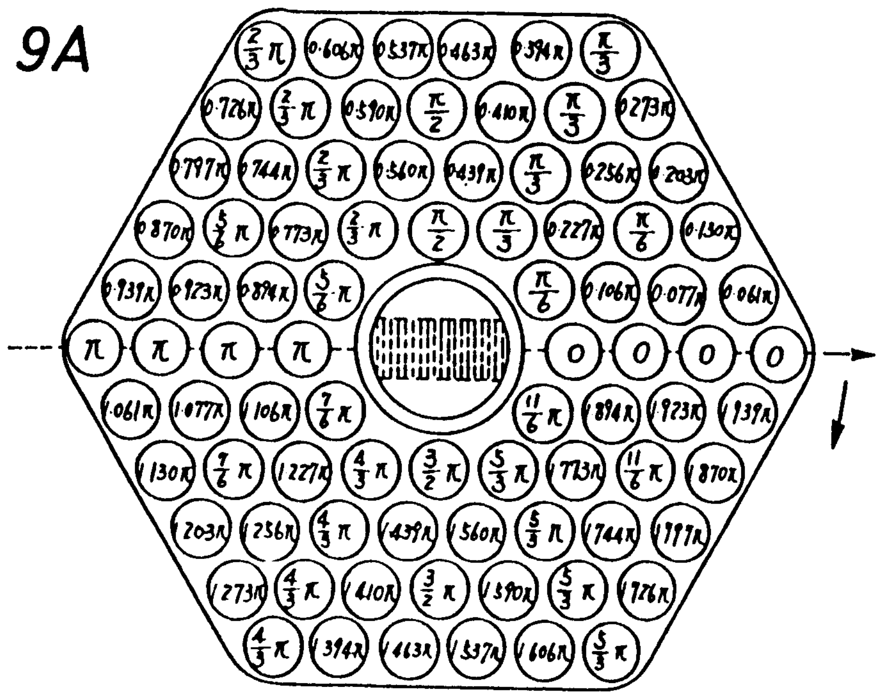


FIG. 9B

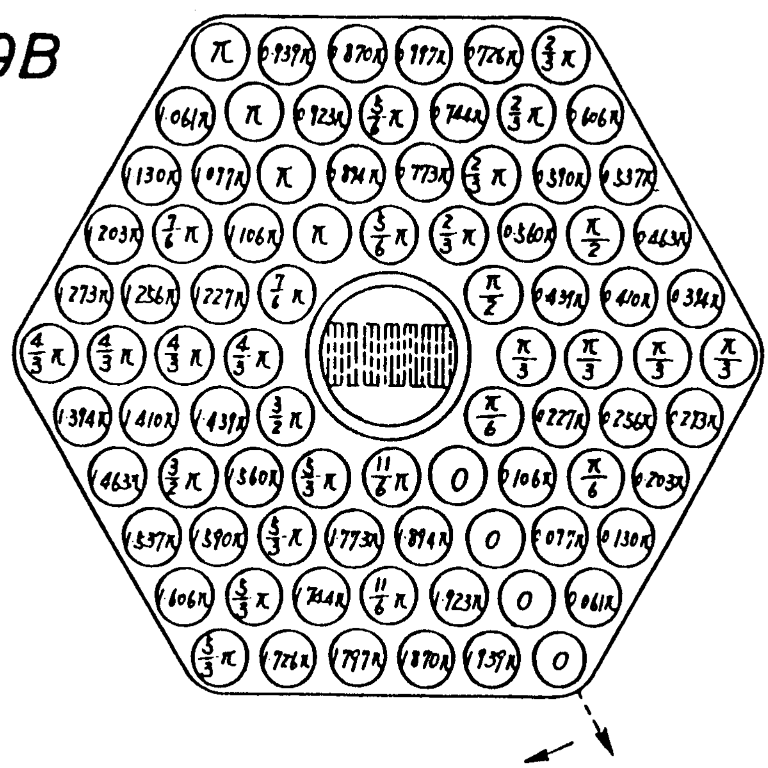


FIG. 10A

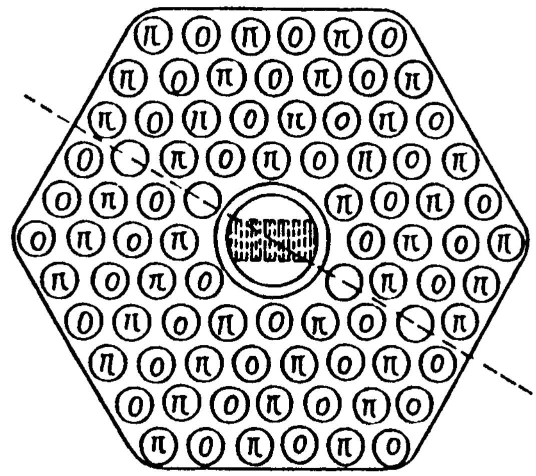


FIG. 10B

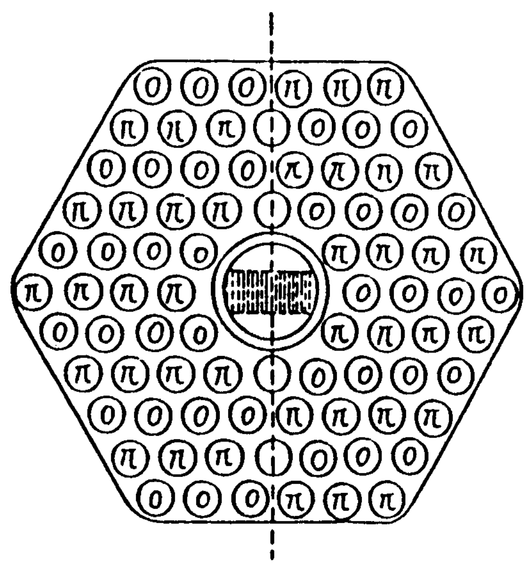


FIG. 10C

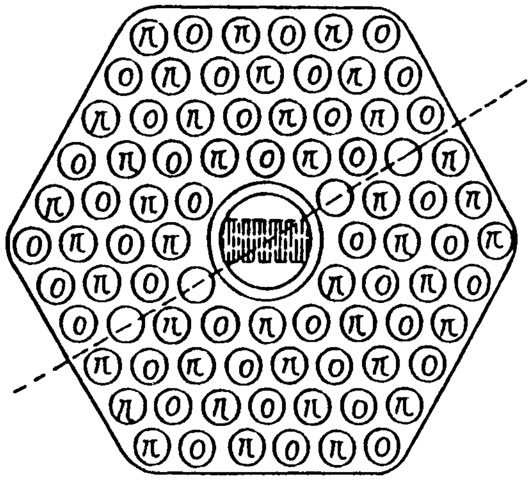


FIG. 11A

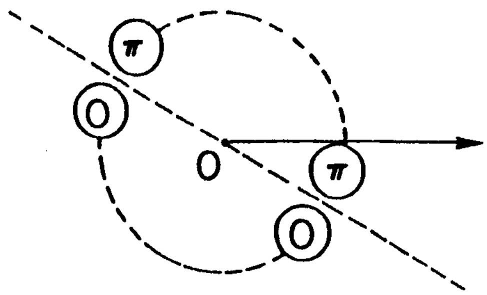


FIG. 11B

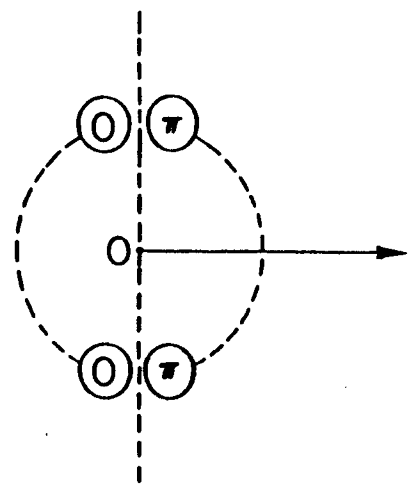


FIG. 11C

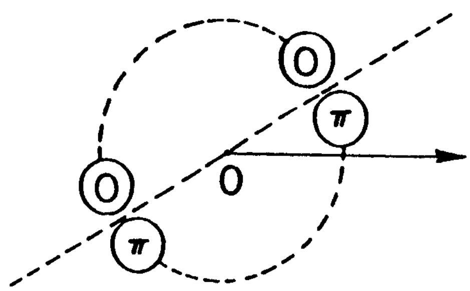


FIG. 12A

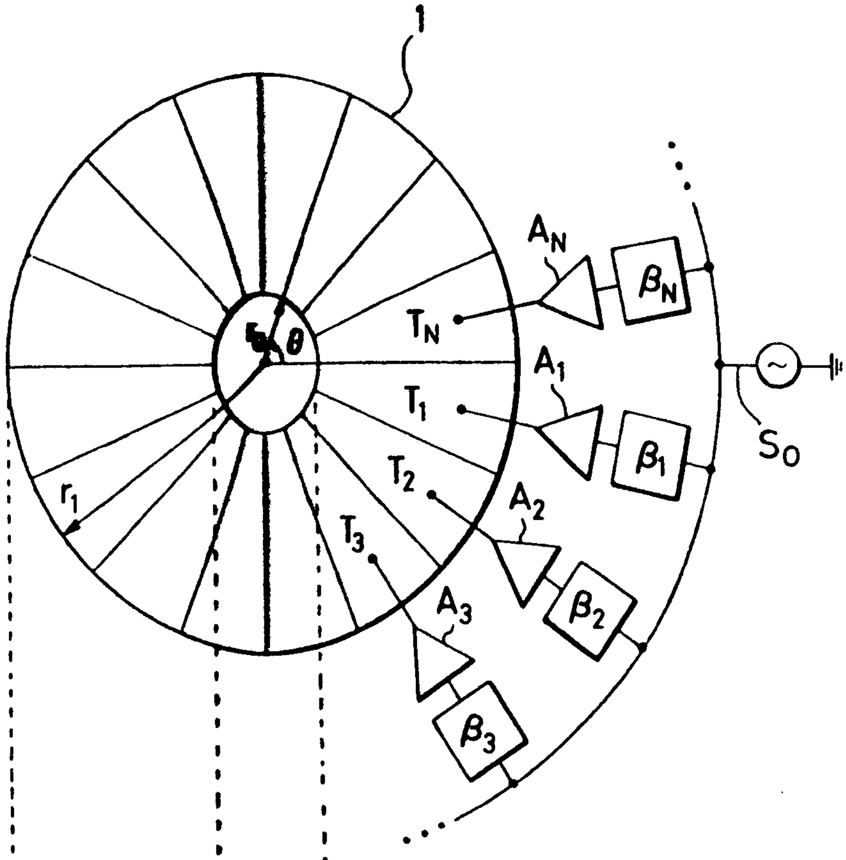


FIG. 12B

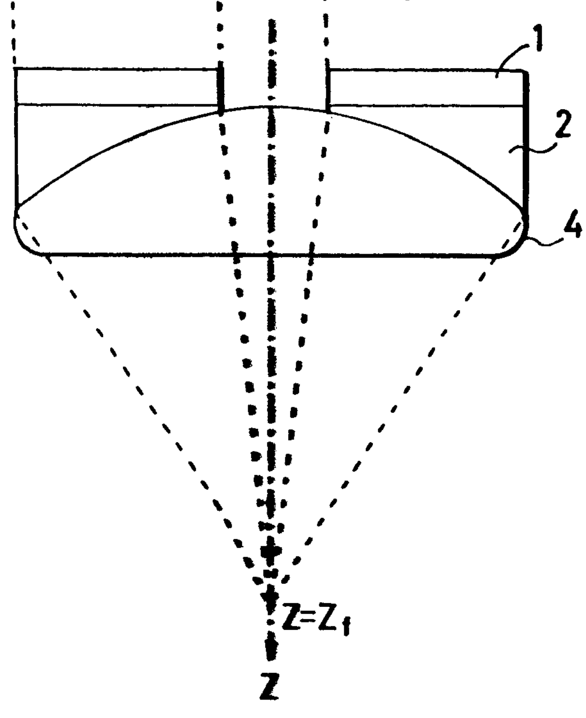


FIG. 13A

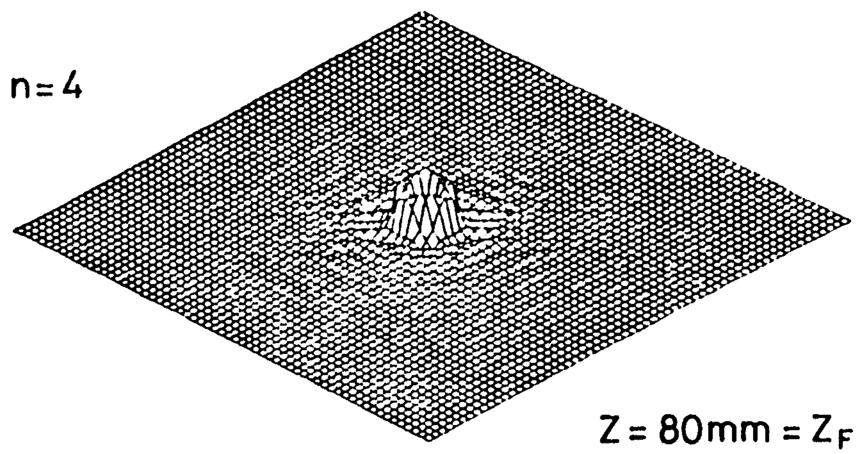


FIG. 13B

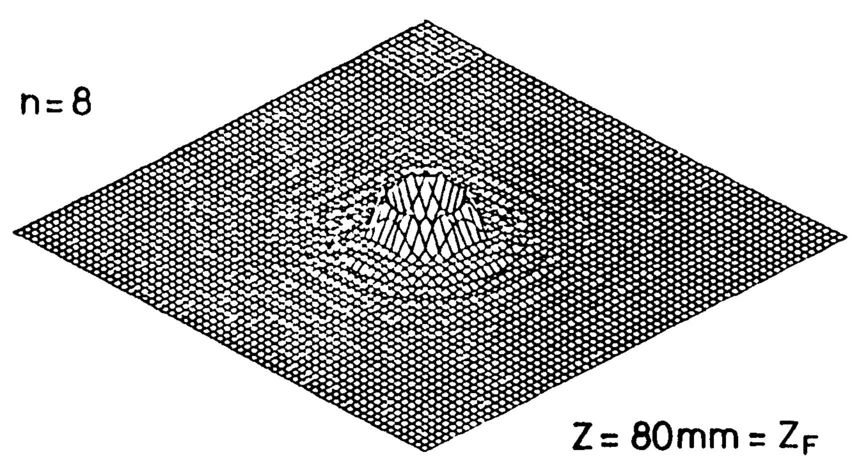


FIG. 14A

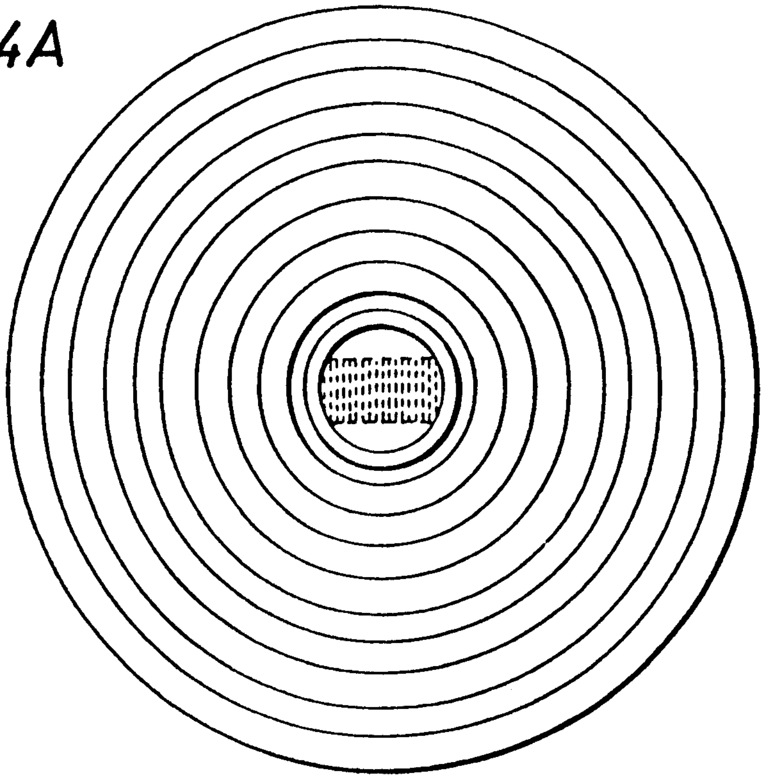


FIG. 14B